

Development of Lightweight Dual Frequency/Polarized Microstrip Antenna Arrays on Organic Substrates

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Abstract- This paper presents the most recent results towards the development of a lightweight dual frequency/polarization microstrip antenna array on Liquid Crystal Polymer (LCP) substrates for NASA's remote sensing applications. LCP's multi-layer lamination capabilities, excellent electrical and mechanical properties, and near hermetic nature make it an excellent candidate for the development of low cost, flexible antenna arrays with integrated RF MEMS switch phase shifters for NASA's applications up to 110 GHz. To test the viability of LCP at these frequencies, several transmission lines were characterized from 2 – 110 GHz on LCP for the first time and a 14 GHz prototype patch array was developed. Initial designs and full-wave simulations have also been performed for a 4-bit RF MEMS phase shifter.

I. INTRODUCTION

It is the NASA Earth Science Enterprise's (ESE) goal to develop a scientific understanding of the Earth's environmental system and its response to natural and man-made changes, which will enable better prediction of climate, weather, and natural hazards. This will lead to expanded and accelerated realization of economic and societal benefits. However, to achieve these goals, NASA and the scientific community needs to develop and adopt advanced technologies to accurately monitor and measure the global precipitation, evaporation, and cycling of water. To monitor precipitation patterns, NASA requires dual-frequency (14/35 GHz for rain and 19/37 GHz for snow), dual-polarization radar and radiometers. The common requirement in these radars is the need for low-cost, low mass, deployable antennas with large surface area that can be rolled-up or folded for launch and then deployed in space. In addition, electronic scanning and shaping of the radiation patterns at the different frequencies is also desirable. For this purpose, we plan to develop a prototype 2x2 dual frequency/polarization microstrip antenna array on an organic substrate (liquid crystal polymer) with integrated RF MEMS phase shifters operating at 14/35 GHz.

Liquid Crystal Polymer (LCP) has recently received much attention as a high frequency circuit substrate and package material. LCP has impressive electrical characteristics that are environmentally invariant due to extremely low water absorption [1], and it provides a nearly static dielectric constant across a very wide frequency range [1, 2]. Thermal expansion characteristics are equally desirable. For circuit applications, the controllable coefficient of thermal expansion (CTE) can be engineered to match either copper or silicon [3]. LCP is flexible, recyclable, impervious to most chemicals, and it is stable up to its high melting

temperature (280°C or 335°C). In addition, LCP is much cheaper than traditional materials such as Kapton, Teflon, and LTCC [3, 4]. It is, therefore, an ideal candidate for low-cost phased arrays that can easily be folded or rolled for deployment in space. These benefits also enable LCP to compete favorably in many other existing and future markets.

LCP research to date has focused mainly on process related issues. Processes have been developed that allow LCP films to be manufactured consistently with good uniformity and strength. Important issues such as copper-LCP adhesion and via formation/plating have also greatly improved over the course of the last year. These advances have facilitated multilayer lamination and vertical integration capabilities. As a result, fabrication of multilayer LCP-based circuits is now becoming a feasible and repeatable process. However, the potential of LCP in microwave and mm-wave devices and circuits has not been fully explored from a materials characterization standpoint.

In this paper we focus on the design, fabrication and measurement of transmission lines on LCP in order to characterize the material through W-band frequencies and verify its suitability for NASA's precipitation radars. In addition, we will present simulated and measured results from a prototype 1x2 14/35 GHz antenna sub-array, and simulations for a 4-bit RF MEMS phase shifter.

II. ARRAY DESIGN AND SIMULATED RESULTS

In order to implement a dual-frequency/dual-polarization antenna array for remote sensing of precipitation at 14/35 GHz, we propose to make use of a two-layer sub-array that consists of two 2x2 uniformly spaced square patch antennas. In the first stages of our research, a 1x2 sub-array will be developed and characterized to extract useful design guidelines for the development of the 2x2 array. Except for the length and number of elements the array would be similar to the one required by the NASA's precipitation radar. The array to be used at 14 GHz has the largest physical size, has a square configuration and it is placed at the interface of the LCP and the air. The second array (to be used at the 35 GHz band) is smaller physically and is embedded between two layers of LCP of equal thickness (~250 μm). A schematic of the proposed solution can be seen in Fig. 1. To avoid parasitic coupling between the two arrays, the second array has a cross configuration, which in reality is a square configuration that is rotated by 45 degrees with respect to the shape of the top array. In addition to this spatial rotation, Electromagnetic Band Gap (EBG) structures, such as via-holes, are embedded in the substrate to reduce coupling between the two sets of microstrip patch antennas and the feeding networks. Since this

2x2 array employs only canonical shapes, it can be fabricated in a quite straightforward way and easily cascaded in both longitudinal and transverse directions. Preliminary theoretical derivations show that 24 arrays of this type could provide a beamwidth smaller than 2 degrees. Furthermore, the LCP substrate allows for the integration of RF MEMS switch based phased shifters for electronic scanning and shaping of the antenna pattern.

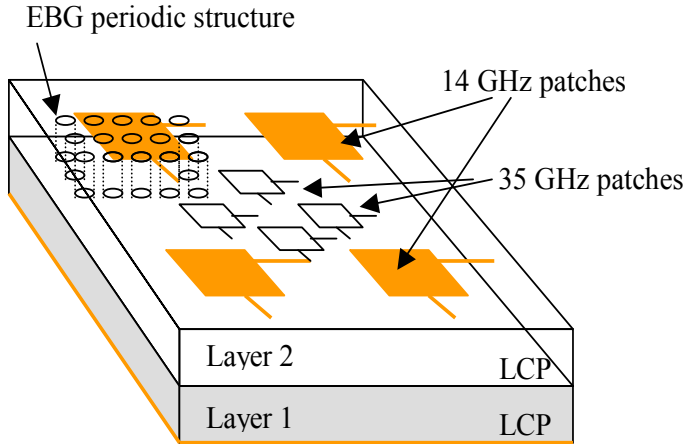


Figure 1. The proposed 2x2 dual frequency/polarization patch antenna array on multi-layer LCP substrate.

The first step in the development of the 1x2 sub-array was the design and experimental characterization up to 110 GHz of various transmission lines. For this purpose, a variety of Finite Ground Coplanar (FGC) Waveguide lines with and without conductor (ground) backing were designed. The FGC line is a modified version of the coplanar line, where the ground planes have finite width. The schematic of a conductor backed FGC line is shown in Figure 2. The line designs were selected to accomplish several goals. The first consideration was to ensure compatibility with 150 μm pitch ground-signal-ground (GSG) 110 GHz RF probes. The CPW probe contacts are excellent for high frequency measurements, but they require relatively small circuits for proper contact. The ground contacts from the probe should have a minimum spacing of 50 μm between the contact point on the ground plane and edge of the gap. In addition, most designs were geared toward a 50 Ω characteristic impedance to closely match that of the network analyzer. LCP substrates of 50 μm , 100 μm , and 200 μm from Rogers Corporation were available for selection. The material parameters for the Rogers LCP substrate are summarized in Table 1.

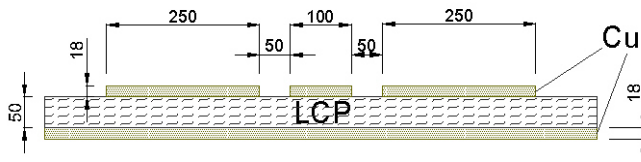


Figure 2. Conductor backed FGC line designed for high frequency characterization of the LCP material. (All dimensions in microns)

Cu clad	Cu Thickness	ϵ_r	$\tan \delta$
Double	18 μm	2.9	0.002

Table 1. Rogers Corporation LCP Parameters

Based on these material parameters, preliminary designs of the dual frequency/polarization 1x2 sub-array at 14/35 GHz were also performed. Each layer thickness was assumed to be 200 μm , with the 14 GHz antennas on the top metal layer and the 35 GHz antennas on the middle layer. For the polarization selection, a single-pole-double-throw (SPDT) switch will be integrated on the LCP substrate. For the purpose of analysis, the ON and OFF states of the switches were approximated by their corresponding capacitances, 2 pF and 20 fF, respectively. A small ($\sim 0.3 \Omega$) series resistance was also assumed in the switch model. A schematic of the 1x2 sub-arrays is shown in Fig. 3. The full-wave simulations were performed with *EmPicasso* and *Microstripes*.

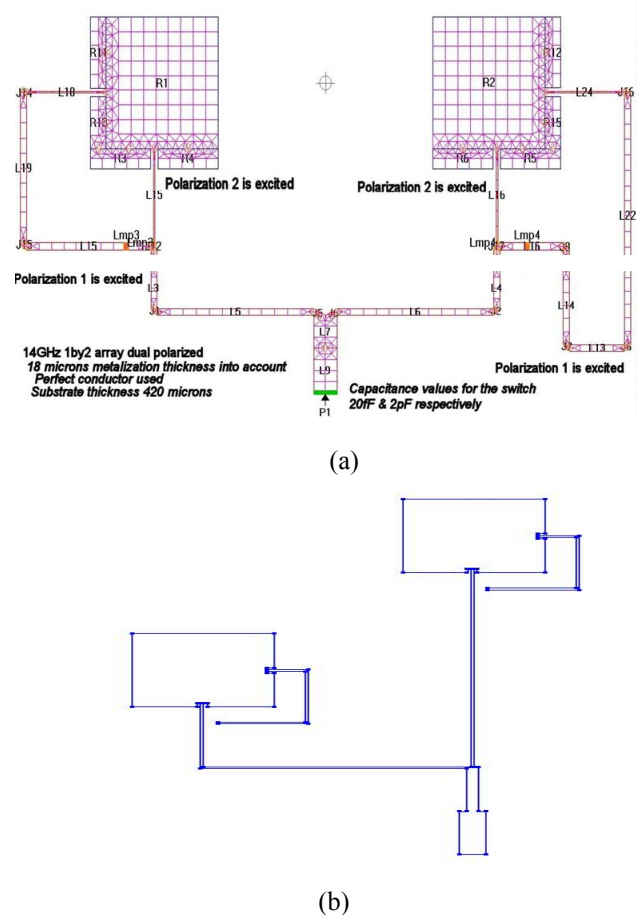
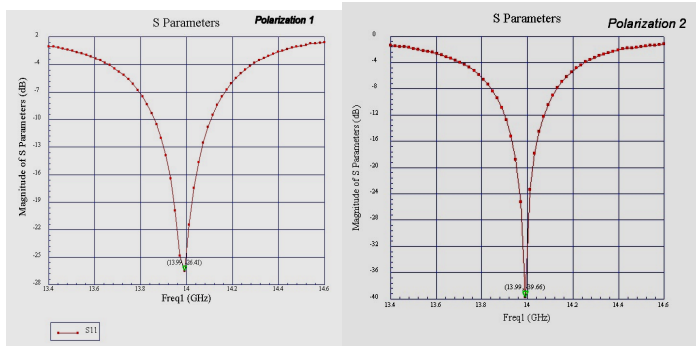
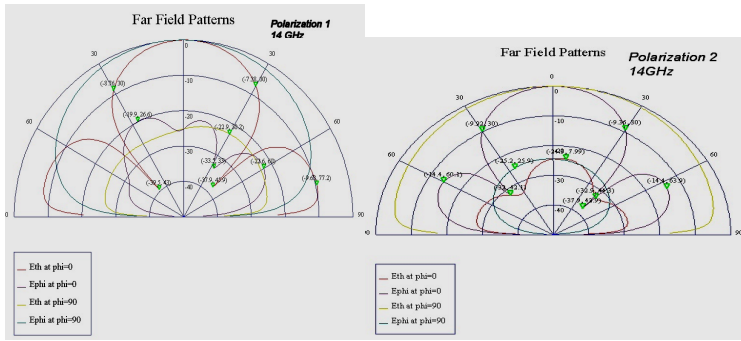


Figure 3. Schematic of the simulated 1x2 sub-array for: a) 14 GHz and b) 35 GHz.

Simulated results for the return loss and the radiation patterns of the 1x2 sub-arrays are summarized in Figs. 4-5, where a very good performance can be observed.

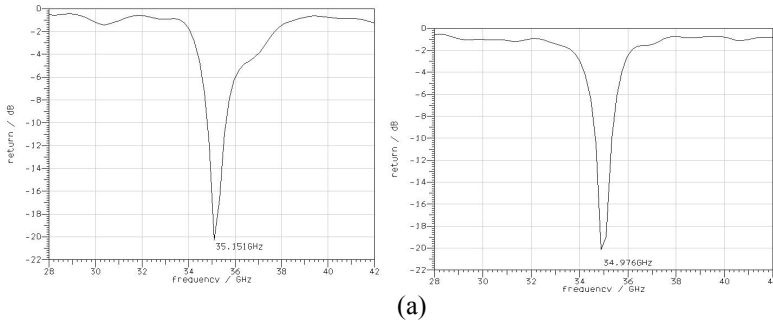


(a)

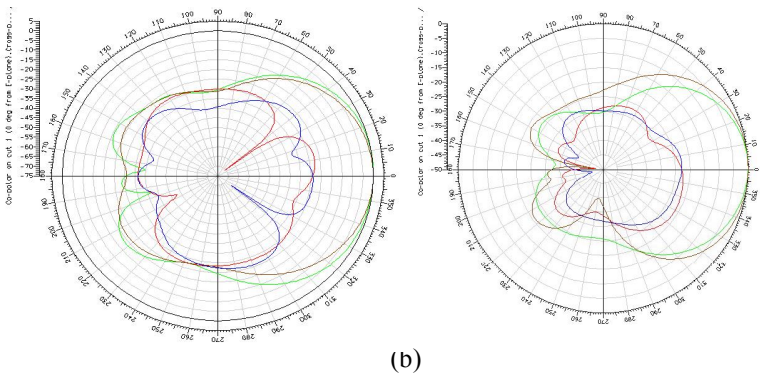


(b)

Figure 4. Simulated results for the 1x2 14 GHz sub-array (2 polarizations): a) return loss and b) radiation patterns.



(a)



(b)

Figure 5. Simulated results for the 1x2 35 GHz sub-array (2 polarizations): a) return loss and b) radiation patterns.

The last component that was analyzed was the RF MEMS switch and the 4-bit phase shifter that will be used for the

electronic control of the array. The phase shifter will be fabricated and characterized first on high resistivity silicon since a lot of expertise already exists for this substrate between Georgia Tech and NASA Glenn. A single-pole-single-throw (SPST) air-bridge switch can be seen in Fig. 6, while the 4-bit phase shifter is shown in Fig. 7. The switch consists of a thin metal membrane suspended 2-3 μm above the substrate. When the switch is electrostatically actuated, the membrane collapses onto the FGC line and creates an electrical short circuit, which reflects the RF power. A thin dielectric layer prevents stiction between the two metals when the switch is pulled down. Designs were optimized for 14 and 35 GHz operation and simulated results for 14 GHz showed an isolation better than 40 dB for the DOWN state and an insertion loss less than 0.5 dB for the UP state. To keep the circuit size small, simulations were performed to determine the minimum required spacing between FGC lines while maintaining less than 30 dB of coupling. A distance of $\lambda/6$ was sufficient for minimal coupling. Simulated results indicate that a return loss better than 15 dB can be achieved for all four paths and insertion loss is less than 0.1 dB per bit. For integration with the antenna arrays the phase shifters will also be fabricated with microstrip lines or alternatively they will include appropriate FGC-to-microstrip transitions.

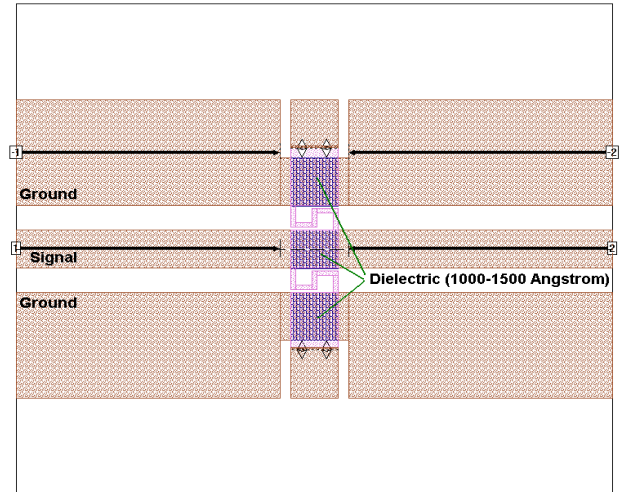


Figure 6. Schematic of SPST air-bridge MEMS switch.

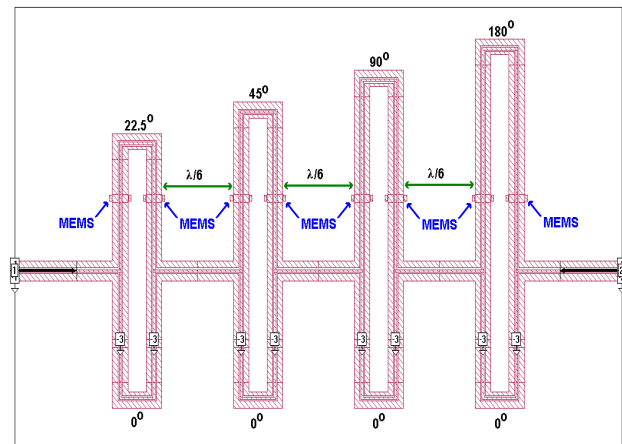


Figure 7. Schematic of 4-bit MEMS phase shifter at 14 GHz.

III. FABRICATION

The transmission line designs and the 14 GHz sub-array were fabricated on LCP substrate using a standard photolithographic process and a wet chemical etch. For the antenna array, two layers were laminated together. Photos of the fabricated circuits and their pliability are shown in Figure 8.

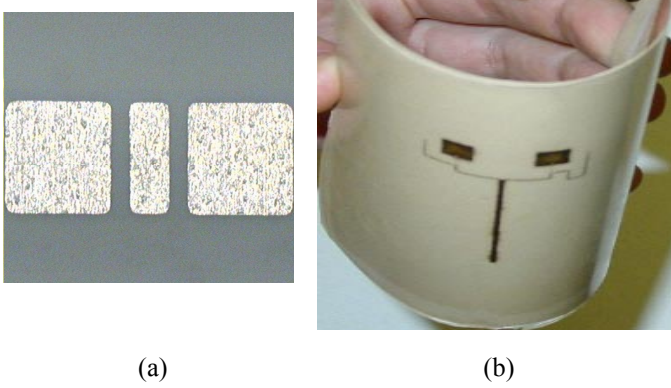


Figure 8. Photos of fabricated: a) FGC transmission line and b) 1x2 14 GHz patch antenna sub-array.

IV. MEASURED RESULTS

An Agilent 8510XF VNA fitted with Cascade Microtech 150 micron pitch probes was used to carry out the FGC line measurements. *Multical* and *HP BASIC* Version 6.32 were used to collect the calibration data from the VNA and de-embed the error terms. 401 data points (maximum) were taken across the valid sweep range from 2 – 110 GHz. 20 samples were taken at each frequency and averaged to achieve stable results. Measurements from the various fabricated lines can be seen in Figs. 9-11. The attenuation measurements of Figs. 9-10 show the very small loss characteristics of the LCP substrate even up to W-band, with attenuation values ranging from 1.3 to 1.8 dB/cm were measured for the regular FGC line and from 1 to 2 dB/cm for the conductor backed FGC. These values are similar to FGC lines of the same geometry fabricated on GaAs, which is a traditional mm-wave substrate. To our knowledge this is the first report for LCP.

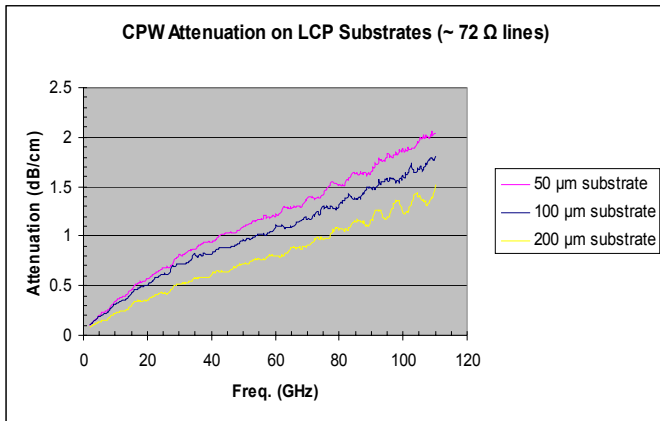


Figure 9. Measured attenuation vs. frequency for a 72 Ω FGC line on LCP substrate with varying thickness.

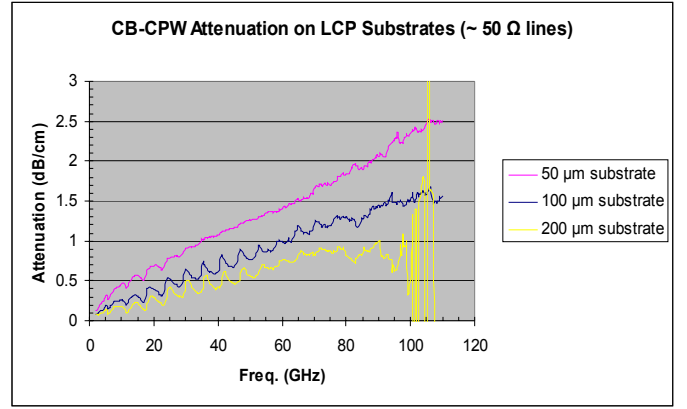


Figure 10. Measured attenuation vs. frequency for a 50 Ω CBFGC line on LCP substrate with varying thickness.

Furthermore, Figs. 11-12 show that an almost pure TEM mode propagates in these transmission lines since the effective dielectric constant is almost flat versus frequency. This allows us to model the aforementioned lines as ideal transmission lines with known attenuation and effective permittivity. As such, the design of phase shifters and feeding networks can be simplified significantly.

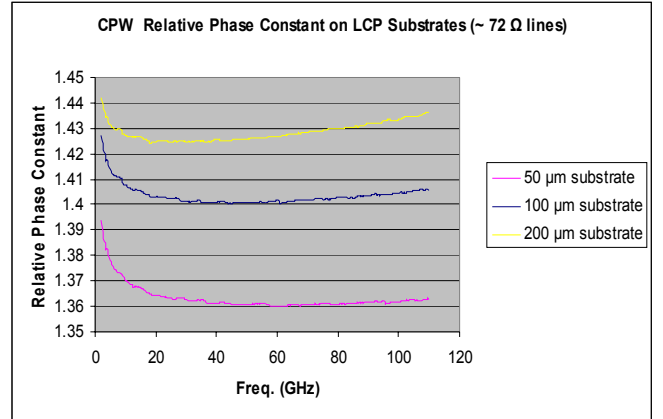


Figure 11. Measured effective dielectric constant vs. frequency for a 72 Ω FGC line on LCP substrate with varying thickness.

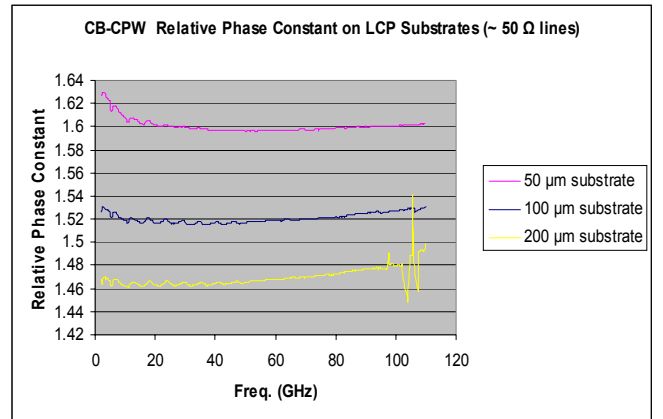


Figure 12. Measured effective dielectric constant vs. frequency for a 50 Ω CBFGC line on LCP substrate with varying thickness.

As a verification step, after performing the TRL calibration, an S-parameter measurement was performed of a 0.24 cm long, FGC delay line. Since the through line length was 500 μm , a reference plane 250 μm from the end of each line is implied. Thus, the 0.24 cm line would then be expected to measure like a 0.19 cm line. S-parameter results are shown in Fig. 13.

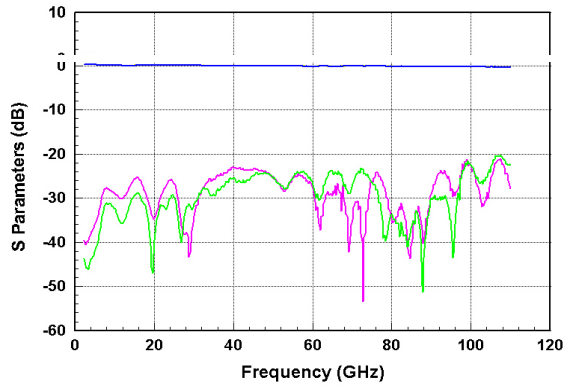


Figure 13. S-Parameter measurement data of the 0.24 cm line after calibration

S_{11} and S_{22} are below -20 dB everywhere and even below -30 dB at several frequencies, indicating good measurement repeatability. S_{21} and S_{12} are the same across the measured frequency band as is expected for symmetric devices. At 110 GHz, the 0.24 cm line was expected to have an attenuation of $(2.235 \text{ dB/cm}) * (0.19 \text{ cm}) = 0.42465 \text{ dB}$ based on the previously presented data in Figure 9. The measured S_{21} value read from the data of Figure 13 at 110 GHz is -0.41207 dB. These numbers are in agreement within 0.0126 dB, which shows the calibration is accurate.

Measurements were also taken for the fabricated 1x2 14 GHz sub-array. The array was mounted on an aluminum fixture that included a coaxial-to-microstrip connector to facilitate the s-parameter measurement. An SOLT calibration was performed with the reference planes at the end of the coaxial cables. Return loss results are shown in Fig. 14.

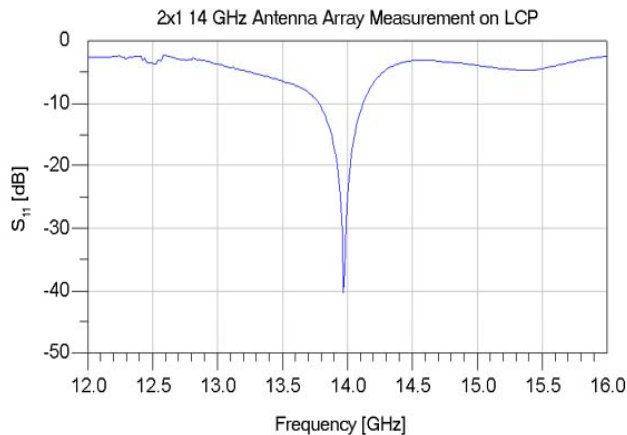


Figure 14. Measured return loss for 14 GHz 1x2 sub-array.

As it is shown in Fig. 14, the return loss is better than 30 dB for polarization #2 of figure 3a. In this implementation the SPDT switches were replaced with perfect open and short sections of transmission line.

V. CONCLUSIONS

This paper presented the most recent results towards the development of a low cost, flexible and low-loss dual frequency/polarization patch antenna phased array on LCP substrate for the 14/35 GHz precipitation radar. Finite ground coplanar lines were characterized up to 110 GHz and measured attenuation ranged from 1.3 dB/cm up to 2 dB/cm for different line geometries and different substrate thickness. A prototype 1x2 14 GHz sub-array was also fabricated on two LCP layers and exhibited better than 30 dB of return loss. Simulated results have also been obtained for the RF MEMS switch and 4-bit MEMS phase shifter that will be used for electronic scanning of the radiation pattern.

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